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Numerical Simulation Study on Characteristics of Overflowing Smoke under Sprinkler Spray

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Abstract

Aiming at the "cabin" fire safety design concept in large space buildings, and combined with a real cabin with a spray system, Large Eddy Simulation was used for simulating the flow state of cabin fire smoke under sprinkler spray. The effect of sprinkler spray on overflowing smoke layer and the characteristics of overflowing smoke under sprinkler spray were analyzed and discussed. Results showed that sprinkler spray had a good cooling effect on smoke layer, but it made smoke layer unstable at the same time, leading to the smoke congestion phenomenon. As a result, smoke spillage was added, and the characteristics of overflowing smoke were significantly changed.

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Keywords:sprinkler spray, cabin,the characteristics of overflowing smoke

1. Foreword

In recent years, with the development of our national economy, there have been more and more large space buildings such as airport terminals, waiting halls and large exhibit centers. These large space buildings can't be designed by general prescriptive regulations. In order to research the phenomenon of uneven distribution of fuel which leads to some areas of high fire load in large space buildings, "cabin" fire safety design concept was put forward in the 1990s. In the concept, the areas of high fire load in large space buildings are separated to form cabins[1,2]. Sprinkler spray in the cabin can not only inhibit fire growth, but also effectively reduce temperature[3-5]. However, its effect on smoke control is not clear yet.

Up to now, many scholars have researched sprinkler spray in cabin. For example, You Yu-hang et al. had researched fire characteristics in cabin under sprinkler[6-8], Li Kai-yuan and Zhang Cun-feng, et al. had researched smoke stability under sprinkler[9,10], and Ji Yuan has researched the effect of sprinkler to fire-fighting and smoke in cabin[11]. These researches mainly focused on the effect of sprinkler spray on cabin fire and smoke. However, the influence of cabin smoke on large space buildings depends on the characteristics of overflowing smoke, so it should be studied.

Compared with the theoretical analysis and full-scale experiments, numerical simulation can easily set physical parameters, initial conditions and boundary conditions. At the same time, it has advantages of short run cycle, high maneuverability, low cost, visualization and simpleness. So it has significance for fire hazard analysis[12].

This paper uses Large Eddy Simulation(LES) to simulate cabin fire in large space and analyzes the simulation results in order to study the influence of sprinkler spray on gas flow velocity, smoke mass flux, temperature, visibility and smoke spillage at the cabin door.

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2. FDS Modeling

A simulation program named FDS developed by NIST was used in this paper[13]. Simulation model was a cabin in large space test hall of State Key Laboratory of Fire Science in USTC. Simulating scenario was set as shown in Fig. 1.The length, width and height of the cabin were 3m, 4m and 3m respectively. The width of the cabin door was 1.6m and the height was 2m. Environment temperature was 20℃. The sprinkler was located at the top center of the cabin. Flow rate of the sprinkler was 80L/min and its activation time was 240s. A block of wood crib was located in the center of the ground and it was about 0.6m×0.6m×0.4m. The combustion reaction properties of the wood crib were set as spruce's properties. An ignition source with area of $0.01m^2$ was located blow the wood crib to ignite the wood crib, and it was removed after 20s. There were six gas-phase devices in the axis of the cabin door, and their heights were 0m, 0.4m, 0.8m, 1.2m, 1.6m and 1.8m, respectively. They were set to measure gas flow velocity, smoke mass flux, temperature and visibility. In addition, a flow measuring device was set in the vertical plane of the cabin door to measure smoke spillage.

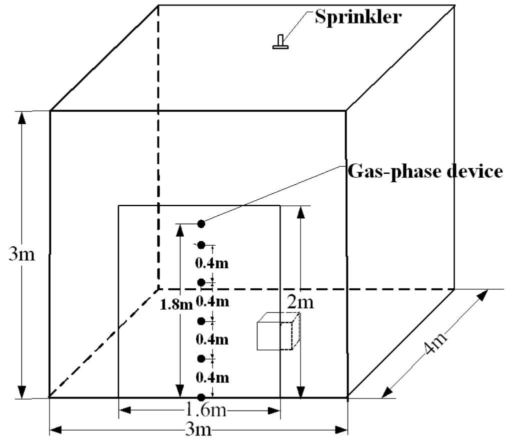

Fig. 1. Cabin model.

3. Simulation analysis

3.1. Description of simulation process

After the fire happened, the upward plume above the fire source entrained lower cold air into upper smoke layer. Outdoor air entered lower air layer of the cabin through the cabin door to supply air. Before the sprinkler activated, smoke layer was stable. As smoke was accumulating, the height of smoke layer decreased. As can be seen in Fig. 2(a), the height of smoke layer decreased to around 1.5m at 240s, and the thickness of overflowing smoke was about 0.5m meanwhile. After the sprinkler activated, smoke layer was unstable, as shown in Fig. 2(b). The smoke in spray coverage area was affected by drag force of water droplets, and the downward drag force was greater than the upward buoyancy, causing the downward congestion jet. When the jet reached the ground, it spread along the ground and formed horizontal smoke flow. As a result, smoke spreading towards the cabin door was discharged through the door.

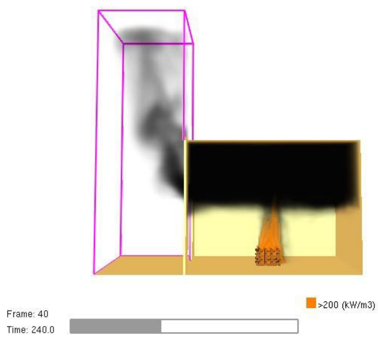

Fig. 2(a). Flow state of smoke before sprinkler activated(240s).

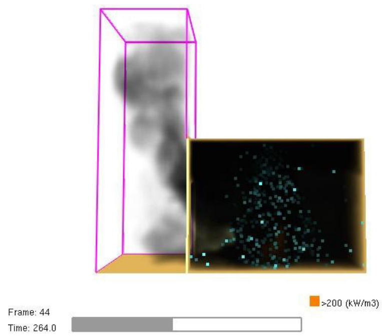

Fig. 2(b). Flow state of smoke after sprinkler activated(264s).

3.2. Gas flow velocity in the axis of the cabin door

As shown in Fig. 3, before the sprinkler activated, gas flow velocity of the two gas-phase devices at 1.8m and 1.6m was positive, indicating that gas flowed out from the cabin through the cabin door. While the values of the other four gas-phase devices were negative. It manifested that smoke layer was stable and outdoor air flowed into air layer below smoke layer of the cabin.

As soon as the sprinkler activated, gas flow velocity at both 1.8m and 1.6m decreased by about 0.7m/s and then increased again. The value at 0.0m changed from negative to positive abruptly and increased rapidly to 1.2m/s. The phenomenon showed that after the sprinkler activated, part of the smoke in the cabin was influenced by drag force of droplets and moved downwards temporarily instead of discharging at once. It moved to the ground and flowed out from the cabin along the ground. The area near the ground started to exhaust air rather than supplying air. From Fig. 3, the direction of gas flow velocity changed at 1.2m. It was likely caused by descending smoke layer and need to be confirmed combining with the figure of smoke mass flux.

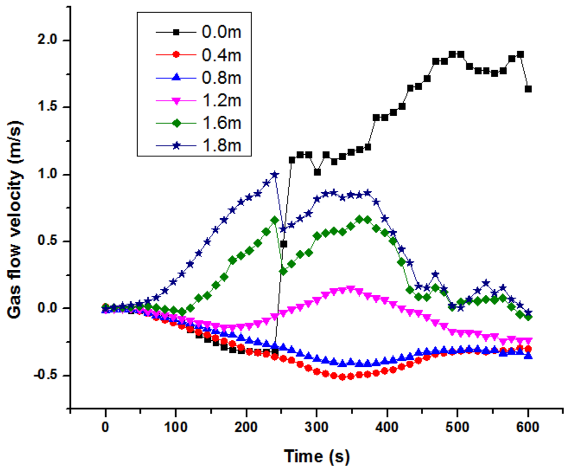

Fig. 3. Gas flow velocity variation with time.

3.3. Smoke mass flux in the axis of the cabin door

As can be seen in Fig. 4, before the sprinkler activated, smoke mass flux at only 1.8m and 1.6m was positive, which indicated that only the two gas-phase devices lied in overflowing smoke layer. Smoke at 1.8m began to overflow at 80s, and that at 1.6m began at 160s. The phenomenon that smoke at 1.8m began earlier was due to the descending smoke layer, and smoke mass flux at 1.8m was always larger than that at 1.6m within 240s. Besides, at this stage, the values of the other four gas-phase devices located at 0.0m~1.2m were null, showing that there was no smoke overflowing below smoke layer.

After the sprinkler activated, smoke mass flux at 0.0m increased rapidly to peak, namely 0.0003kg/s/m^2. It manifested that downward congestion jet which was caused by droplets flowed out along the ground. At the same time, the value at 1.2m increased from null, indicating that smoke layer descended to a height less than 1.2m due to spray. Compared with the value before 240s, the height of smoke layer decreased by at least 0.3m. It just explained why the direction of gas flow velocity at 1.2m was changed in Fig. 3. Moreover, Fig. 4 showed that the direction of smoke mass flux at 0.4m and 0.8m was negative and the two values kept lower than 0.000025 kg/s/m^2, indicating that after the sprinkler activated, when air was supplied at 0.4m and 0.8m, it entrained part of smoke which was discharged along the ground into the cabin.

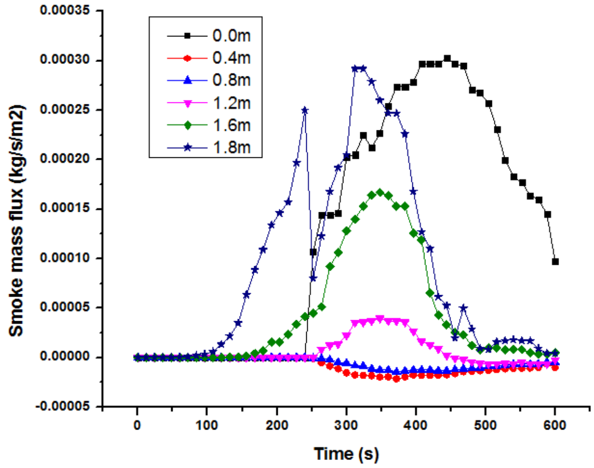

Fig. 4. Smoke mass flux variation with time.

3.4. Temperature in the axis of the cabin door

As Fig. 5 showed, before the sprinkler activated, temperature at 1.8m began to increase at 50s and increased to maximum 130℃ at 240s, while the value at 1.6m began at 130s and increased to 76℃ at 240s. Temperature at 1.8m increased earlier and was always higher than that at 1.6m. Before 240s, temperature of the other four gas-phase devices located at 0.0m~1.2m stayed around environment temperature(20℃). It showed that overflowing smoke layer kept stable without spray as well as temperature of upper smoke layer was higher, and outdoor air flowed into the cabin below overflowing smoke layer.

As soon as the sprinkler activated, temperature at 1.6m and 1.8m decreased remarkably. The value at 1.8m decreased to 45℃ and that at 1.6m decreased to 37℃, indicating that spray had a good cooling influence on hot smoke layer. After 240s, temperature at 0.4m and 0.8m was always close to environment temperature. It can also illustrate the phenomenon that outdoor air flowed into the cabin at the two heights. Temperature at the other four heights was higher than 20℃, showing there was smoke flowing out. And the higher the height was, the higher the temperature was.

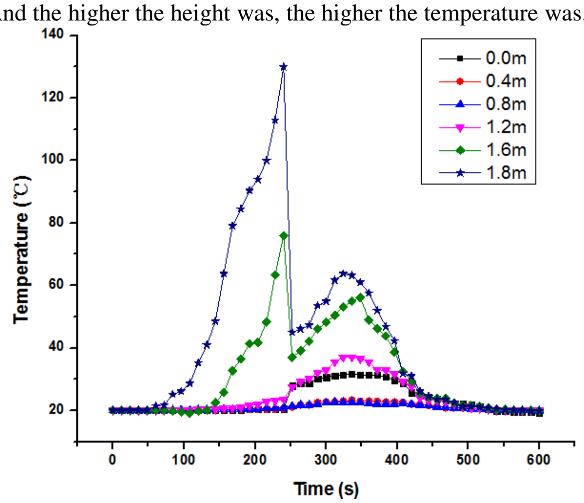

Fig. 5. Temperature variation with time.

3.5. Visibility in the axis of the cabin door

As can be seen in Fig. 6, before the sprinkler activated, there was smoke overflowing the cabin only at 1.8m and 1.6m. As smoke layer descended, visibility at 1.8m firstly decreased at 70s, and then visibility at 1.6m decreased at 140s. At 240s, visibility at both 1.8m and 1.6m decreased to 2.5m. Before 240s, visibility at 1.8m was always lower than that at 1.6m.It showed that visibility decreased with the increase of height under no spray. While visibility at the other four heights was almost invariably and maintained about 30m, illustrating that no indoor smoke overflowed but outdoor air flowed into the cabin. It was consistent with the conclusion above.

After the sprinkler activated, visibility at 1.8m and 1.6m had no remarkable change. However visibility at 0.0m decreased rapidly from 30m to 2.5m, which showed that there was a lot of mixture of smoke and vapor spilling out. Visibility at 0.4m and 0.8m was higher than that at the other four height, but was lower than the value before sprinkler activated, because when the outdoor air flowed into the cabin, it entrained some smoke discharged along the ground into the cabin. Besides, the height of smoke layer descended to lower than 1.2m and there was smoke overflowing, so it can be seen in Fig. 6 that visibility at 1.2m decreased fast to about 3m after 240s.

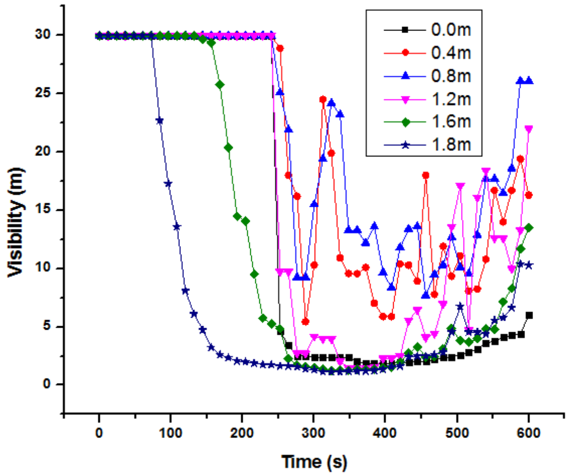

Fig. 6. Visibility variation with time.

3.6. Smoke spillage at the cabin door

It was showed in Fig. 7 that smoke spillage at the cabin door increased steadily from 0 to 0.85 m^3/s within 240s. As soon as the sprinkler activated, the spillage decreased to 0.65 m^3/s at once, but then it increased again until reaching the peak 1.0 m^3/s. The phenomenon that smoke spillage decreased at 240s in Fig. 7 occurred because part of indoor smoke moved forwards under drag force instead of spilling out through the cabin door immediately. When forward smoke reached the ground, it moved horizontally and flowed out from the cabin. Therefore, smoke spillage continued to increase. Moreover, the addition of water vapor promoted smoke to mix with vapor so that mixture of smoke and vapor was generated. It resulted in increase of total smoke as well as descend of smoke layer, due to which smoke spillage continuously increased to peak 1.0m^3/s.

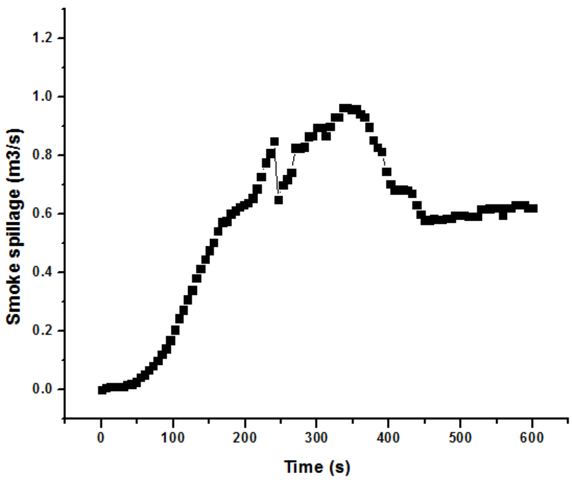

Fig. 7. Smoke spillage variation with time.

4. Conclusion

Before the sprinkler activated, smoke layer was stable. As smoke accumulated, the height of smoke layer decreased. And the thickness of overflowing smoke was about 0.5m at 240s. Outdoor air flowed into the air layer of the cabin through the cabin door to supply air source. Only the data of the gas-phase devices in overflowing smoke layer changed remarkably, while the data of the other devices had no significant change.

After the sprinkler activated, smoke layer was unstable. The downward drag force of smoke in spray coverage area was greater than the upward buoyancy, causing the downward congestion jet. Meanwhile smoke layer descended, and smoke spillage was added, and the scope of air supply was narrowed. When outdoor air flowed into cabin, it entrained part of smoke discharged along the ground into the cabin. During this process, all measured data at the ground surface changed noticeably and the characteristics of overflowing smoke were significantly changed.

Although temperature of the smoke overflowing to large space buildings drops remarkably under sprinkler spray, overflowing smoke buoyancy diminishes at the same time, and it turns out that smoke is difficult to discharge from large space buildings. What's more, smoke congestion caused by spray speeds up decline of smoke so that visibility decreases rapidly. As a result, available safety egress time is shortened. Therefore, this study suggests that reasonable sprinkler systems should be designed to achieve rapid and efficient fire extinguishing purpose. In addition, mechanical exhaust systems should be installed if necessary to avoid smoke spilling out of the cabin.

Acknowledgements

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